

Experimental evidences of a large extrinsic spin Hall effect in AuW alloy.

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(Dated: March 28, 2014)

We report an experimental study of a gold-tungsten alloy (7% at. W concentration in Au host) displaying remarkable properties for spintronics applications using both magneto-transport in lateral spin valve devices and spin-pumping with inverse spin Hall effect experiments. A very large spin Hall angle of about 10% is consistently found using both techniques with the reliable spin diffusion length of 2 nm estimated by the spin sink experiments in the lateral spin valves. With its chemical stability, high resistivity and small induced damping, this AuW alloy may find applications in the nearest future.

The spin Hall effect (SHE) [1, 2] is an emerging route for spintronics since it allows for conversion of charge into pure spin currents or *vice-versa* through the direct or inverse SHE [3] in non-magnetic materials. For instance, pure spin currents without a net charge current can be produced this way but require materials with strong spin-orbit (SO) interaction, beyond solely Pt [4–7] or Pd [8]. The conversion ratio between the charge and spin currents is called the spin Hall angle (θ_{SHE}). The SHE was first observed in semiconductor materials using optical methods [9, 10]. More recently, reported values of a few percent in metals revived the subject [4] and led to an investigation of several metals and alloys with reported spin Hall angle value as large as 30% [11]. Despite the large dispersion of spin Hall angle and a long standing debate about the results [7, 12, 13], experiments showed that the spin current produced by the spin-orbit effects can be successfully used in order to electrically control magnetization *via* spin-torque switching of ferro-magnets [7, 13] as well as precession in spin-torque ferromagnetic resonance [14]. Additional proposition are the stirring effect [15], the spin Hall effect transistors along gated semiconductor channels [16], or the charge production for spin caloritronics [17]. An important challenge for applications is to find materials with an efficient spin to charge current conversion. Large θ_{SHE} of intrinsic origin were predicted theoretically [18, 19] and confirmed experimentally [20] in 4d and 5d transition metals. The extrinsic SHE however, through either the skew-scattering [21] or the side jump [22] mechanism, allows even better control of the θ_{SHE} by tuning the impurity concentration in a host material [23] and taking advantage of resonant scattering on impurity levels split by the spin orbit interaction [24]. Therefore, even larger effects in doped materials with suitable host and impurities with large SO interaction could be foreseen, as was recently found in CuIr [25], CuBi [26] or CuPb [27]. These materials can act as building blocks for new spintronics applications such as spin current injectors or detectors as demonstrated through CuIr Magnetic Tunnel Junctions (MTJ) [28], write heads [29] or Giant-SHE-MTJs [30].

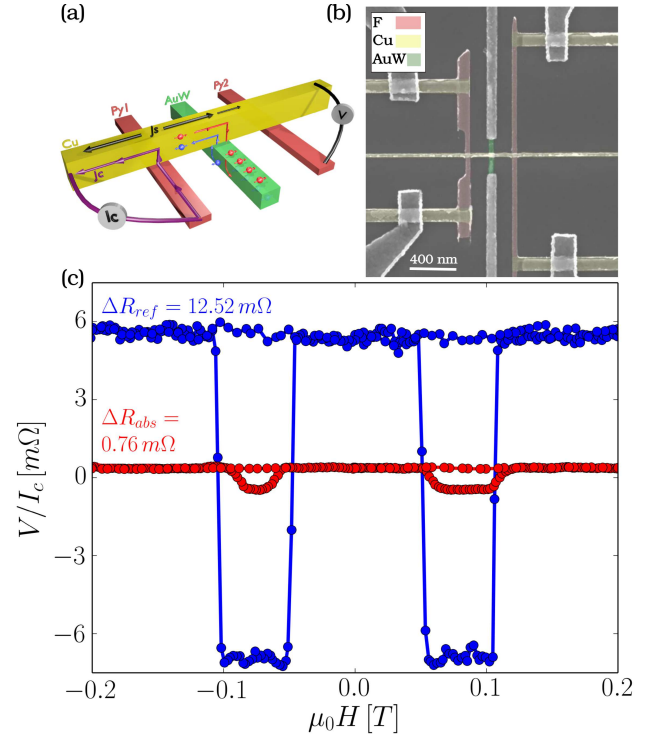


Figure 1. (a) Schematic representation and (b) a Scanning Electron Microscope image of a lateral spin valve fabricated using multi-angle shadow evaporation technique with AuW_{7%} nano-wire inserted in-between two Py ferromagnets. Spin signal recorded at $T = 11 \text{ K}$ for nano-structures with (red) and without (blue) AuW_{7%} nano-wire insertion.

In this letter we present analyses of a metallic AuW alloy (7% at. W concentration in Au host - controlled using particle-induced X-ray emission technique) exhibiting a large θ_{SHE} , using two complementary methods: lateral spin valves and inverse spin Hall effect (ISHE) along with spin pumping. The first method consists of the lateral spin valves (LSV) experiments allowing characterization of materials with small spin diffusion length [31].

Figure 1 represents (a) a sketch and (b) a scanning electron microscope image of a typical device fabricated using

the multi-angle nano-fabrication method [32], where the colors red, yellow, and green represents ferromagnetic, non-magnetic and SHE material respectively. First, the middle $AuW_{7\%}$ wire is deposited on the SiO_2 substrate using Physical Vapor Deposition (PVD) and a lift-off technique, followed by the nano-fabrication of a Py/Cu lateral spin-valve. In between these two steps the middle wire surface is cleaned using Ar ion-milling. The Py, Cu and $AuW_{7\%}$ nano-wires are 20 nm, 70 nm and 20 nm thick respectively. Their width is fixed to 50 nm with an exception of the 100 nm wide $AuW_{7\%}$. The distance separating the ferro-magnets in the presented device is $L = 400$ nm (from center to center of ferro-magnets).

Non-local measurements have been performed, using a standard Lock-in amplifier technique at $f = 79$ Hz, for two types of nano-structures. The first one as a reference is a regular non local device [32] including a Cu channel and two ferromagnetic Py electrodes whereas the second one includes a $AuW_{7\%}$ wire inserted in between the ferromagnetic electrodes [Fig. 1(a-b)]. In these experiments a spin accumulation is created in the LSV by passing a partly spin-polarized charge current through a ferromagnetic/non-magnetic interface ($Py1/Cu$) [Fig. 1(a)]. The spin accumulation diffuses in both directions from this interface in Cu giving rise to spin currents. On the right-hand side of the LSV there are only pure spin currents without a net charge flow (J_s black arrows) which are partially absorbed by the $AuW_{7\%}$ nano-wire. The voltage is measured across the second $Py2/Cu$ interface in order to probe spin currents arriving at this interface. The amplitude of the spin signal for reference and absorption devices was measured to be $\Delta R_{ref} = 12.52$ m Ω and $\Delta R_{abs} = 0.75$ m Ω respectively which yields an absorption of 94% (independent of temperature) [Fig. 1(c)].

These experiments allow the experimental evaluation of the spin diffusion length of $AuW_{7\%}$ to be determined as long as the absorption ration is known. The resistivity of the inserted material, ρ_{SHE} , can be directly measured, however the spin diffusion length needs to be calculated. For the general case of the LSV, using a 1D model [31, 33], the ratio of the spin signal amplitude with the middle wire to the spin signal amplitude without this nano-wire equals [34]:

$$\frac{\Delta R_{ref}}{\Delta R_{abs}} = \frac{(R_N + \exp(L/l_{sf}^N)(R_F + R_N))R_{AuW}}{R_N(-R_N + R_{AuW}) + \exp(L/l_{sf}^N)(R_F + R_N)(R_N + R_{AuW})} \quad (1)$$

Here $R_{N(F)} = \rho_{N(F)} l_{sf}^{N(F)} / A_{N(F)} (1 - P_F^2)$ stands for spin resistances, where: $A_N = w_N \times t_N$, $A_F = w_F \times t_F$, $\rho_{N(F)}$, $l_{sf}^{N(F)}$, t_N , $w_{N(F)}$, $A_{N(F)}$ are the resistivity, the spin diffusion length, the thickness, the width and the effective cross sectional area respectively. In the presented notation subscripts F and N correspond to the ferromagnetic and non-magnetic material respectively. The spin resistance of the inserted $AuW_{7\%}$ nano-wire is:

$$R_{AuW} = \frac{\rho_{AuW} l_{sf}^{AuW}}{w_N w_{AuW} \tanh(t_{AuW}/l_{sf}^{AuW})}$$

This allows for l_{sf}^{AuW} of the AuW nano-wire to be extracted knowing material characteristic parameters of the LSV: AuW resistivity $\rho_{AuW_{7\%}} = 570 \Omega \cdot nm$ and thickness $t_{AuW_{7\%}} = 20$ nm. Remaining LSVs parameters are: $\rho_{Cu}^{11K} = 55 \Omega \cdot nm$, $\rho_{Py}^{11K} = 118 \Omega \cdot nm$, and the characteristic spin transport parameters: $l_{sf}^{Cu} = 320$ nm and $P_{eff} = 0.36$, which were taken from our previous experiments [35–37]. These results are in agreement with what can be found in literature for similar structures [38]. This analysis leads to the spin diffusion length of $AuW_{7\%}$ to be $l_{sf}^{AuW_{7\%}} = 1.9$ nm.

Moreover, one can also perform SHE experiments in the very same structure. A spin current is injected electrically by using $Py1/Cu$ interface as presented above. The spin current absorbed by the $AuW_{7\%}$ nano-wire is then converted into a transverse charge current *via* the SHE and thus leads to an electric voltage signal. The external magnetic field is swept along the non-magnetic Cu channel while a voltage drop is measured on the $AuW_{7\%}$ nano-wire edges.

Figure 2 shows experimental data-points obtained at $T = 11$ K for the Inverse-SHE when the voltage is measured at the edge of the AuW wire and Anisotropic Magneto-resistance (AMR) in 2 contacts at the edge of the Py injector. Probe configurations are represented schematically in corresponding insets. A clear non-local signal is observed yielding $\Delta R_{SHE} = 0.1$ m Ω . Its amplitude is a roughly linear function of the magnetic field in a region below the saturation field $\mu_0 H_{sat} = 0.38$ T which corresponds to the situation where the magnetization of the ferromagnetic injector (Py1) is fully parallel to the non-magnetic Cu channel.

It is known that evaluating the spin Hall angle with a simple 1D model leads to underestimation of the θ_{SHE} due to the shunting effect [25, 26]. We then performed a more sophisticated analysis using a Finite Element Method (FEM) simulation [35]. The result of this analysis shows that the spin Hall angle $\theta_{SHE}^{AuW_{7\%}(3D)} = 10\%$ is larger than the one obtained with the 1D model ($\theta_{SHE}^{AuW_{7\%}(1D)} = 1\%$) [39]. Two effects contribute to underevaluation of the $\theta_{SHE}^{AuW_{7\%}}$ with the 1D model. The main effect is due to shunting by the Cu layer of a part of the ISHE current produced by the spin current absorption in AuW nano-wire. The current distribution is quite inhomogeneous and therefore one should take into account only a shunt by a part of the Cu layer in the same order of magnitude than about half the contact width. This leads to the 1D model correction factor of about 12 (related directly with the AuW/Cu resistivity ratio). This can be view in figure 3 where 90% of the current extends on about 18 nm in Cu layer. This emphasizes the 1D model limitation with these aspect ratios and the requirement to use a finite element model in order to analyze the data correctly. The second effect is linked to

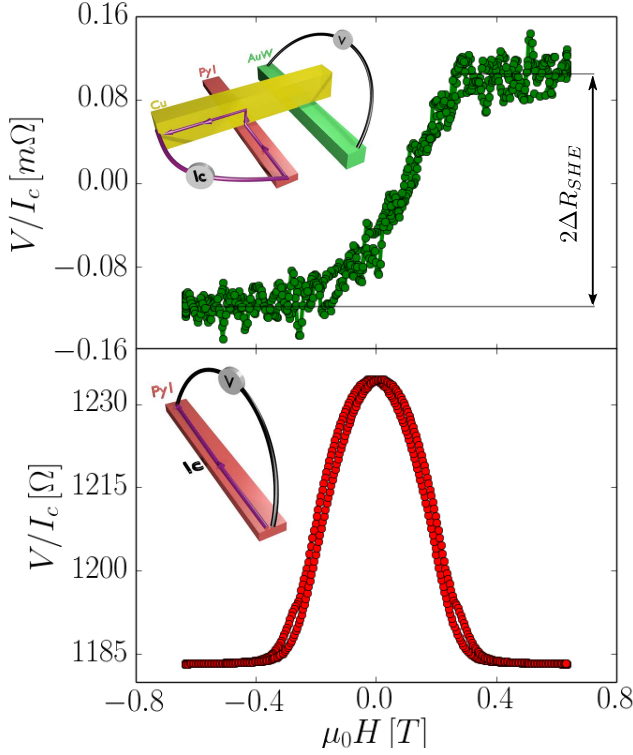


Figure 2. (a) Inverse-SHE measurements in $AuW_{7\%}$ 100 nm width nano-wire with (b) Anisotropic-Magnetoresistance signal of the ferromagnetic injector, both measured at $T = 10$ K. External magnetic field was applied along the non-magnetic channel direction. The saturation field in both figures correspond. (Insets) Schematic representation of used measurement configurations.

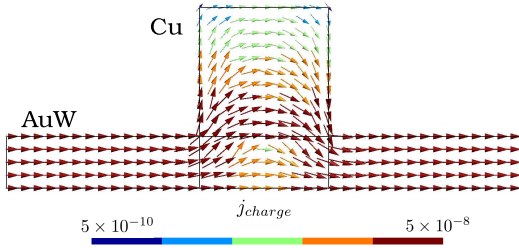


Figure 3. Cross section of the AuW/Cu interface charge current distribution using FEM simulations represented in the logarithmic scale.

the spreading of the spin accumulation over the sides of the contacts in the SHE material mainly when the spin diffusion length of the SHE materials is long, compared to the width. In our case with a spin diffusion length of about 2 nm compared to the thickness of 20 nm, this effect should be negligible giving a posteriori justification of the derivation of the $l_{sf}^{AuW_{7\%}}$ with 1D model [Eq. 1].

We turn now to the second experiment performed at room temperature: spin pumping and ISHE where the ferromagnetic resonance (FMR) is exploited. The re-

sistivity variation from 10K up to 300K for $AuW_{7\%}$ is $\Delta\rho/\rho \sim 3\%$, almost insensitive to temperature due to the dominant role of the scattering by impurities. We thus expect $l_{sf}^{AuW_{7\%}}$ (as well as $\theta_{SHE}^{AuW_{7\%}}$) to be independent of the temperature and that the two measurement results can be directly compared. We have grown by sputtering a $\parallel Py(15\text{ nm})/AuW_{7\%}(30\text{ nm})$ bilayer, and a $\parallel Py(15)/Al(7\text{ nm})$ reference sample. In a usual FMR experiment, a microwave is applied at a given frequency and power with a magnetic field strength h_{rf} . Additionally, a perpendicular dc magnetic field $\mu_0 H_{dc}$ is swept. At the resonance condition, when $\mu_0 H_{dc}$ is parallel to the film plane, a pure dc spin current is injected from the Py layer to the $AuW_{7\%}$ layer. This is the spin pumping effect [40] which can be detected by the increase of the damping constant in the bilayer with respect to the single Py reference sample. Due to the ISHE in the $AuW_{7\%}$ layer, the injected dc spin current is converted into a dc charge current, which, in turn, can be detected as a transverse dc voltage.

A typical schematic of the spin pumping-ISHE experiment is shown in Fig. 4(a). As described previously [41, 42] we have used a broadband stripe system to accurately determine the damping constant [Fig. 4(b)] and we have used an X-band cylindrical cavity to measure the FMR spectrum and the voltage due to the ISHE [Fig. 4(c)]. The frequency f vs. magnetic resonant field, $\mu_0 H_{res}$, allows the effective magnetic saturation and in plane anisotropy to be calculated as displayed in Fig. 4(b) top. We can observe that both samples, the $\parallel Py/Al$ reference and the $\parallel Py(15\text{ nm})/AuW_{7\%}(30\text{ nm})$ bilayer have the same M_{eff} value and a negligible in-plane magnetic anisotropy ($\mu_0 H_{uni}$). The linear frequency dependence of the peak-to-peak linewidth ($\Delta(\mu_0 H_{pp})$) allows extraction of the damping constant α and the f -independent contribution $\Delta(\mu_0 H_0)$, due to inhomogeneities. A linear behavior is found on both samples in the whole experimental range [Fig. 4(b) bottom]. Furthermore, the contribution due to inhomogeneities is very small, $\Delta(\mu_0 H_0) < 0.1\text{ mT}$, and a small but clear increase of the damping constant for $\parallel Py(15\text{ nm})/AuW_{7\%}(30\text{ nm})$ can be observed (with respect to the reference sample). Thus we can conclude, that the $AuW_{7\%}$ layer acts as a spin sink layer. This can be verified in the simultaneously $FMR - V_{dc}$ measurement [Fig. 4(c)], where we can observe a symmetrical Lorentzian voltage peak at the resonance field.

In order to quantify the spin Hall angle of this material we use all our experimental values taking advantage of the spin diffusion length already determined in the previous section (which is invariant of temperature). The effective spin mixing conductivity is calculated as [40, 43]: $g_{eff}^{\uparrow\downarrow} = \mu_0 M_{eff} t_F (\alpha_{F/N} - \alpha_F) / (g \mu_B) = 5.9 \times 10^{18}\text{ m}^{-2}$, where $F(N)$ stands for $Py(AuW_{7\%})$ layer, $\mu_0 M_{eff} = 0.97\text{ T}$ is the effective demagnetization field, g is the Landé g -factor, μ_B is the Bohr constant, t_F is 15 nm,

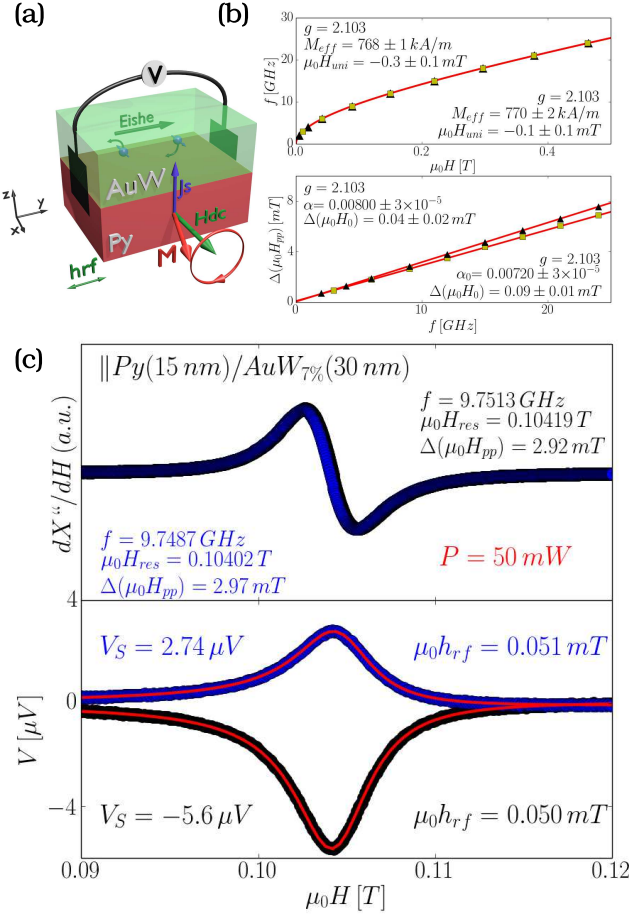


Figure 4. (a) A sketch of the $\text{Py}(15\text{ nm})/\text{AuW}_{7\%}(30\text{ nm})$ sample at the resonance condition. A spin current is injected from the Py layer into the $\text{AuW}_{7\%}$ layer. Due to the inverse spin Hall effect the spin current is converted into a charge current and detected by measuring the transverse dc voltage. Experimental data for (b) the frequency dependence of the resonance field (top) and of the peak-to-peak linewidth (bottom) after FMR spectrum measurements in a broadband frequency range. Lines represent fits of Kittel's relationship (top) and a Gilbert-type damping contribution (bottom). Fitted values are displayed in each panel. (c) The FMR spectrum and the dc voltage measured simultaneously at 9.75 GHz in a cylindrical resonant cavity. The $\mu_0 h_{rf}$ value was measured with samples inside the cavity. Black dots represent the peak-down voltage data in the parallel case, while blue ones represent the case of sample turned 180 degrees in-plane (anti-parallel). Lines show for a Lorentzian fits of the voltages. The symmetrical voltage amplitude V_S is displayed for each case.

and all other values are shown in Fig. 4(b). The effective spin current density injected at the $\text{Py}/\text{AuW}_{7\%}$ interface, while considering a transparent interface (no spin decoherence), is given by [8, 43, 44]:

$$J_S^{\text{eff}} = \left(\frac{2e}{\hbar} \right) \frac{g_{\text{eff}}^{\uparrow\downarrow} \gamma^2 \hbar (\mu_0 h_{rf})^2}{8\pi \alpha_{F/N}^2} \left[\frac{\mu_0 M_{\text{eff}} f \gamma + \sqrt{(\mu_0 M_{\text{eff}} f \gamma)^2 + 4\omega^2}}{(\mu_0 M_{\text{eff}} f \gamma)^2 + 4\omega^2} \right] \quad (2)$$

where e is the electron charge, \hbar is the Dirac constant, $\gamma = g\mu_B/\hbar$ and $\omega = 2\pi f$. Considering $f = 9.75\text{ GHz}$ and $\mu_0 h_{rf} = 0.1\text{ mT}$, we obtain $J_S^{\text{eff}} = 3.4\text{ MA/m}^2$. In order to eliminate undesirable effects [42, 45] the dc transverse voltage amplitudes in between two dc magnetic field directions have been averaged and weighted by $(\mu_0 h_{rf})^2$. We obtain a value of 1650 V/T^2 . Independently, we have measured the sheet resistance of the bilayer, $R_S = 9.95\text{ }\Omega/\text{sq}$, which gives the resistance of $L \times W = 2.4 \times 0.4\text{ mm}^2$ sized sample to be $59.7\text{ }\Omega$. Then the dc charge current weighted by $(\mu_0 h_{rf})^2$ is $I_C/(\mu_0 h_{rf})^2 = 28\text{ A/T}^2$. The conversion between the spin current density J_S^{eff} and the charge current due to the ISHE is expressed by [8, 43, 44]:

$$I_C = -W \theta_{SHE}^{\text{AuW}_{7\%}} l_{sf}^{\text{AuW}_{7\%}} J_S^{\text{eff}} \tanh\left[\frac{t_{\text{AuW}_{7\%}}}{2l_{sf}^{\text{AuW}_{7\%}}}\right] R_{SML} \quad (3)$$

where $t_N = 30\text{ nm}$ is the thickness of the $\text{AuW}_{7\%}$ layer and $R_{SML} \leq 1$ accounts for the spin flip scattering at the $\text{Py}/\text{AuW}_{7\%}$ interface [44]. Considering transparent interface ($R_{SML} = 1$) and using the previous values one obtains a lower boundary for the spin Hall angle of $\text{AuW}_{7\%}$, $\theta_{SHE}^{\text{AuW}_{7\%}} = +10\%$, where the “+” indicates the same SHE sign as in Pt. Interface spin resistance and spin memory loss parameters are not yet well known in Py/Au , but the integration of such quantities will necessarily lead to an increase of the determined spin Hall angle [44]. At this point, we cannot state whether the extrinsic SHE is due to skew scattering or side jump. Additional experiments are in progress to elucidate this question. In this study we have also verified that θ_{SHE}^{Au} for pure Au is around 0.4%, which is close to the value reported elsewhere [43]. Despite of the small damping enhancement, comparable with pure Au and Ta, we have estimated a large $\theta_{SHE}^{\text{AuW}_{7\%}}$ which makes this alloy attractive for applications which require a low damping constant.

In summary we have developed a gold alloy with a heavy element in order to increase its spin Hall angle. We have shown by complementary studies, that the spin diffusion length of $\text{AuW}_{7\%}$ is 1.9 nm and its spin Hall angle is at least 10%. This value is more than one order of magnitude higher than in a pure gold and can probably be further increased with higher impurity concentrations. The large spin Hall angle in $\text{AuW}_{7\%}$ makes this material very attractive for future developments of spintronics devices, which incorporate non magnetic materials in order to detect or to generate pure spin currents. In particular, its stability at room temperature and its chemical inertia are technologically advantageous compared to other materials. Future research should investigate the spin memory loss effect at the interface, to determine the dominant scattering mechanism and optimize the W concentration in order to maximize the spin/charge current conversion efficiency.

We acknowledge U. Ebels, S. Gambarelli, and G. Desfonds for technical support with the FMR measurements.

This Work was partly supported by the French Agence Nationale de la Recherche (ANR) through projects SPIN-HALL (2010-2013) and SOSPIN (2013-2016).

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- [1] M. Dyakonov and V. Perel, *Physics Letters A* **35**, 459 (1971).
- [2] J. E. Hirsch, *Phys. Rev. Lett.* **83**, 1834 (1999).
- [3] J. Inoue and H. Ohno, *Science* **309**, 2004 (2005).
- [4] E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, *Applied Physics Letters* **88**, 182509 (2006).
- [5] T. Kimura, Y. Otani, T. Sato, S. Takahashi, and S. Maekawa, *Phys Rev Lett* **98**, 156601 (2007).
- [6] L. Vila, T. Kimura, and Y. Otani, *Phys. Rev. Lett.* **99**, 226604 (2007).
- [7] L. Liu, R. Buhrman, and D. Ralph, *arXiv preprint arXiv:1111.3702* (2011).
- [8] K. Ando and E. Saitoh, *Journal of Applied Physics* **108**, 113925 (2010).
- [9] Y. Kato, R. Myers, A. Gossard, and D. Awschalom, *Science* **306**, 1910 (2004).
- [10] J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth, *Physical review letters* **94**, 047204 (2005).
- [11] L. Liu, C.-F. Pai, Y. Li, H. Tseng, D. Ralph, and R. Buhrman, *Science* **336**, 555 (2012).
- [12] Y. Niimi, D. Wei, H. Idzuchi, T. Wakamura, T. Kato, and Y. Otani, *Physical Review Letters* **110**, 016805 (2013).
- [13] I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, *Nature* **476**, 189 (2011).
- [14] L. Liu, T. Moriyama, D. C. Ralph, R. A. Buhrman, and M. T. R. D. C. B. R. A., *Physical Review Letters* **106**, 36601 (2011).
- [15] Y. V. Pershin, N. A. Sinitsyn, A. Kogan, A. Saxena, and D. L. Smith, *Applied Physics Letters* **95**, 022114 (2009).
- [16] J. Wunderlich, B.-G. Park, A. C. Irvine, L. P. Zârbo, E. Rozkotová, P. Nemeč, V. Novák, J. Sinova, and T. Jungwirth, *Science* **330**, 1801 (2010).
- [17] G. E. Bauer, E. Saitoh, and B. J. van Wees, *Nature materials* **11**, 391 (2012).
- [18] T. Tanaka, H. Kontani, M. Naito, T. Naito, D. S. Hirashima, K. Yamada, and J. Inoue, *Phys. Rev. B* **77**, 165117 (2008).
- [19] H. Kontani, T. Tanaka, D. S. Hirashima, K. Yamada, and J. Inoue, *Phys. Rev. Lett.* **102**, 016601 (2009).
- [20] M. Morota, Y. Niimi, K. Ohnishi, D. H. Wei, T. Tanaka, H. Kontani, T. Kimura, and Y. Otani, *Phys. Rev. B* **83**, 174405 (2011).
- [21] J. Smit, *Physica* **24**, 39 (1958).
- [22] L. Berger, *Physical Review B* (1970).
- [23] A. Fert, A. Friederich, and A. Hamzic, *Journal of Magnetism and Magnetic Materials* **24**, 231 (1981).
- [24] A. Fert and P. M. Levy, *Physical review letters* **106**, 157208 (2011).
- [25] Y. Niimi, M. Morota, D. H. Wei, C. Deranlot, M. Basletić, A. Hamzić, a. Fert, and Y. Otani, *Physical Review Letters* **106**, 126601 (2011).
- [26] Y. Niimi, Y. Kawanishi, D. H. Wei, C. Deranlot, H. X. Yang, M. Chshiev, T. Valet, A. Fert, and Y. Otani, *Phys. Rev. Lett.* **109**, 156602 (2012).
- [27] Y. Niimi, H. Suzuki, Y. Kawanishi, Y. Omori, T. Valet, A. Fert, and Y. Otani, *Phys. Rev. B* **89**, 054401 (2014).
- [28] M. Yamanouchi, L. Chen, J. Kim, M. Hayashi, H. Sato, S. Fukami, S. Ikeda, F. Matsukura, and H. Ohno, *Applied Physics Letters* **102**, 212408 (2013).
- [29] S. Datta, S. Salahuddin, and B. Behin-Aein, *Applied Physics Letters* **101**, 252411 (2012).
- [30] S. Manipatruni, D. Nikonov, and I. Young, *arXiv preprint arXiv:1301.5374*, 1 (2013).
- [31] T. Kimura, J. Hamrle, and Y. Otani, *Phys. Rev. B* **72**, 014461 (2005).
- [32] P. Laczkowski, L. Vila, S. Ferry, A. Marty, J.-M. George, H. Jaffrès, A. Fert, T. Kimura, T. Yang, Y. Otani, and J.-P. Attané, *Applied Physics Express* **4**, 1 (2011).
- [33] H. Jaffrès, J.-M. George, and A. Fert, *Phys. Rev. B* **82**, 140408 (2010).
- [34] Presented formula is a simplified version of the equation from [31].
- [35] P. Laczkowski, *Courants de spin et l'effet Hall de spin dans des nanostructures latérales*, Ph.D. thesis, Grenoble (2012).
- [36] J.-C. Rojas Sánchez, P. Laczkowski, W. Saverio Torres, M. Cubukcu, V. Nguyen, L. Notin, C. Beigné, C. Vergnaud, A. Marty, M. Jamet, *et al.*, *Applied Physics Letters* **102**, 132408 (2013).
- [37] N. Motzko, B. Burkhardt, N. Richter, R. Reeve, P. Laczkowski, W. S. Torres, L. Vila, J.-P. Attané, and M. Kläui, *Physical Review B* **88**, 214405 (2013).
- [38] J. Bass and W. P. Pratt, *Journal of Physics: Condensed Matter* **19**, 183201 (2007).
- [39] S. Takahashi and S. Maekawa, *Science and Technology of Advanced Materials* **9**, 014105 (2008).
- [40] Y. Tserkovnyak, A. Brataas, and B. I. Halperin, *Reviews of Modern Physics* **77**, 1375 (2005).
- [41] A. Jain, J.-C. Rojas-Sánchez, M. Cubukcu, J. Peiro, J. Le Breton, E. Prestat, C. Vergnaud, L. Louahadj, C. Portemont, C. Ducruet, *et al.*, *Physical review letters* **109**, 106603 (2012).
- [42] J.-C. Rojas-Sánchez, M. Cubukcu, A. Jain, C. Vergnaud, C. Portemont, C. Ducruet, A. Barski, A. Marty, L. Vila, J.-P. Attané, E. Augendre, G. Desfonds, S. Gambarelli, H. Jaffrès, J.-M. George, and M. Jamet, *Phys. Rev. B* **88**, 064403 (2013).
- [43] O. Mosendz, V. Vlaminc, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader, and A. Hoffmann, *Physical Review B* **82**, 214403 (2010).
- [44] J.-C. Rojas-Sánchez, N. Reyren, P. Laczkowski, W. Saverio, J.-P. Attané, C. Deranlot, M. Jamet, J.-M. George, L. Vila, and H. Jaffrès, *Phys. Rev. Lett.* **112**, 106602 (2014).
- [45] Z. Feng, J. Hu, L. Sun, B. You, D. Wu, J. Du, W. Zhang, a. Hu, Y. Yang, D. M. Tang, B. S. Zhang, and H. F. Ding, *Physical Review B* **85**, 214423 (2012).